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Techniques for Producing and Measuring Water Drops: A Literature Review

Abstract

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This publication presents and discusses a wide range of references on techniques for producing uniform-sized water drops for calibration purposes and on various techniques for measuring or sizing raindrops or artificially produced water drops. The references were gathered from such diverse fields as meteorology, chemistry, engineering, and fusion physics. Although the publication is intended primarily for use in determining rainfall characteristics and developing and calibrating rainfall simulators, it should prove useful to workers in fields where knowledge of drop-size characteristics is important.

Drop-production techniques include capillary drip, axial airflow, cyclic disturbance, electric atomization, rotating disk, hanging yarn, effervescence, and vibrating reeds. With these techniques, uniform water drops from 0.001 to 20 mm diameter can be produced.

Sizing techniques discussed include filter papers and dye, flour catchment, photo-optical, magnesium oxide, oil catchment, momentum recorders, photography, coated screens, and weighing. Theories behind each of the techniques are briefly presented and applicable drop sizes are noted.

Keywords: Water drops, producing rainfall, rainfall simulators, drop measurement, measuring raindrops, sizing

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Techniques for Producing and Measuring Water Drops: A Literature Review

By M. J. Robinette and D. K. McCool[1]

Introduction

Renewed concern about soil erosion, runoff, and water quality has heightened interest in rainfall simulation. Because rainfall and storm characteristics vary widely across the United States, rainfall simulators must be capable of producing water drops with the characteristics that are typical of the natural rain in the area under study. For characterization of natural rainfall, drop size must be measured and uniform-size water drops produced for calibration purposes. This bibliography of techniques for producing uniform-size drops and measuring drops was assembled for a study of raindrop characteristics in the Pacific Northwest (McCool et al. *1978*).[2] Liquid drops, both naturally and artificially produced, have been studied in many fields, ranging from meteorology and engineering to chemistry and fusion physics.

In our present report, we have evaluated and discussed material from more than 140 publications and have assembled this material into a single reference source for other researchers. We divided the material into two parts. Part one covers several techniques for producing artificial drops of uniform size; the techniques range from simple to complex. The range of uniform drop diameters produced, if specified in the reference, is reported after the reference date. Theoretical bases are outlined for several techniques. Detailed explanations are available in the original sources listed in the bibliography. Part two is concerned with techniques for catching and measuring drops. Sources of error and applicability of each technique are mentioned if they are specified by either the author or by another researcher.

In general, no drop-forming or drop-sizing technique is perfect for all objectives; most techniques were developed for specific research. The reader must consider each of the techniques and choose on the basis of one's needs, time constraints, and resources.

Methods for Producing Uniform Water Drops

Drop production methods reviewed here include capillary drip, axial airflow, cyclic disturbance, electric atomization, rotating disk, hanging yarn, and miscellaneous techniques. The capillary drip and yarn methods are the simplest techniques but do not form water drops less than about 2 mm in diameter. Axial airflow techniques produce drops down to about 0.1 to 0.3 mm diameter, and cyclic disturbance techniques produce drops in the 0.01 to 2.0 mm range. Electric atomization can produce drops of smaller sizes, down to 0.0002 mm. Drops can be spun from a rotating disk, but they are deposited in a circular pattern around the disk. Various other methods are briefly described. For easy reference, all methods, references, and range of drop diameters are summarized in table 1, page 8, at the end of this section.

Capillary Drip

The capillary drip method basically consists of a glass or metal tube with an attached water supply. The water passes through the tube and is retained at its tip until some external force overcomes the surface tension retaining the drop. The method has a practical limit in that capillary tubes of less than 18 gage (0.84 mm i.d.) clog easily and are not dependable (Mutchler *1965*). The earliest recorded use of capillaries to form drops of specific, controlled size began in Europe as a calibration technique for the filter paper method of recording raindrops and rainfall drop size distributions (Defant *1905*; Lenard *1904*; Wiesner *1895*). Bentley (*1904*) used glass capillaries and broomsplints to calibrate his flour-pan-drop-catchment method using drops 2 to 4 mm in diameter. The smaller drops were created by dripping water down the sides of the broomsplints to form a drop at the end. Size was a function of surface tension and splint diameter. Mutchler and Moldenhauer (*1963*) used nested telescoping steel tubes to produce large drops, 3.0 to 5.8 mm in diameter, with a reproducibility of ±1 percent in a rainfall simulator. Mutchler (*1965*) identified factors controlling the size of drops dripping from steel tubes as flow rate, water temperature, surface tension, and inside tube diameter and published tables of test results based on those factors.

Laws (*1941*) and Laws and Parsons (*1943*) used steel capillaries in their studies on drop size vs. terminal velocity and on drop-size distribution in rainfall. They produced drop sizes ranging from 1.17 to 6.1 mm in diameter, but to produce drop sizes of less than 2.3 mm they found it necessary to coat the capillaries inside and outside with paraffin to reduce surface tension effects. Wang and Pruppacher (*1977*) used hypodermic needles to create drops 1.70 to 6.70 mm in diameter to study the effects of air temperature and pressure on the terminal velocity of drops. Hardy et al. (*1960*) report

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[2]The year in italic, when it follows the author's name, refers to Bibliography, p. 12.

creating drops as small as 0.002 mm using an ultra-micro-pipette coated with a solution of trichloro-ethyl-silane in chloroform to reduce retaining forces between the capillary and the drop.

Chow and Harbaugh (*1965*), in a paper on rainfall simulation, reviewed the forces affecting drop formation at the end of a capillary. In a free-body analysis, three forces affect the forming drop. The weight of the drop (F_w) and the force due to velocity of the flow in the capillary tube (F_v) act to remove the drop from the capillary tip while the surface tension (F_s) seeks to retain the drop. When $F_s < F_v + F_w$, the drop leaves the capillary and falls. The resulting drop diameter is defined by

$$d = 61.0\,(\sigma\, d_t)^{1/3} \qquad (1)$$

where d = drop diameter, in millimeters

d_t = inside diameter of capillary, in inches

σ = surface tension, in pounds per foot

This relationship assumes that F_v is negligible so that $F_s = F_w$.[3]

Rainfall simulators with capillaries are described by Adams et al. (*1957*) [5.56 mm],[4] Bubenzer and Jones (*1971*) [2.2 to 4.9 mm], Ekern and Muckenhirn (*1947*) [2.75 to 5.80 mm], and Römkens et al. (*1975*) [2.7 mm].

Axial Airflow

In refinement of the capillary method for producing smaller drops, concentric airflow is applied parallel with the axis of the capillary to help overcome the surface tension that holds the drops to the tip. Lane (*1947*) first used and described such a system. His system consisted of a graduated burette attached to a water reservoir with a drop-forming tip centered and parallel to the axis of an air nozzle. He reported that continuous drop streams of 0.3 mm in diameter and larger were produced with a diameter fluctuation of less than ± 3 percent. Levvy (*1947*) modified Lane's system by introducing a micropiston to control the amount of fluid present at the capillary tip. This apparatus produced single drops of known size. Ennis and James (*1950*) used a similar system to produce drops 0.22 to 1.82 mm in diameter.

Gunn and Kinzer (*1949*) and Kinzer and Gunn (*1951*) [0.07 to 5.76 mm] used concentric airflow devices to study terminal velocity, evaporation, temperature, and thermal relaxation time in free-falling water drops. The mean scatter in mass for the smallest drops was 12 percent and decreased to 2 percent for 2.7 mm drops. Rasbash (*1953*) used a battery of hypodermic needles with individual concentric airflows to produce showers of uniform drops of 0.6- to 2.4-mm diameter in a rainfall simulator. Nonstandard size drops, however, were produced by drop collision and coalescence.

Airflow devices have been used to calibrate recorders that determine distribution of drop size in rainfall. Dingle and Schulte (*1962*) [0.72 to 3.13 mm], Hardy (*1962*) [0.7 to 3.0 mm], and Mason and Ramanadham (*1953*) [0.5 to 1.25 mm] calibrated light-based optical systems, and Englemann (*1963*) [0.6 to 12.0 mm] calibrated an Ozalid paper recording system.

Buckholz (*1957*) [0.3 to 1.6mm] attached a concentric airflow device to a geometric pattern-producing carriage block to apply rectangular patterns of uniform drops to test surfaces and animal skins. Buckholz and McPhail (*1960*) modified the device by extending a 0.1-mm stylus 2.5 mm beyond the end of a 30-gage needle and produced uniform drops from 0.045 to 0.45 mm in diameter.

In attempts to achieve a very small drop size by use of higher and higher air pressure, drop stability and uniformity decrease and satellite drops appear. These phenomena are caused by nonuniform airflow and turbulence in the airstream (Englemann *1963*; Gunn and Kinzer *1949*). Reil and Hallett (*1969*) [0.4 to 2.0 mm] and Samuels and Sparks (*1973*) [0.1 to 3.0 mm] overcame this turbulence problem by pulsing the airflow system at specific, timed intervals. The time of the interval controls the size of the drop, and the pulsing of the air supply eliminates much of the turbulence. Charwat (*1977*) used the principle of axial flow when he used a mixture of mineral oil and carbon tetrachloride as the drop medium and water as the transport mechanism to produce drops 0.2 to 2.5 mm in diameter for flow visualization in hydraulic models.

Cyclic Disturbance

The production of uniform drop size by means of cyclic disturbance was first described by Rayleigh (*1878*). In his discussion on the theory on the instability of jets,

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[3]In this manuscript, symbols and units of the cited publication will generally be used. Since different authors have used the same symbol with different definitions, all symbols in equations will be defined immediately following the equation. If the meaning of a symbol is the same in consecutive equations, the symbol will be redefined only if necessary to assist the reader.

[4]Numbers in brackets indicate drop sizes.

he concluded that the disintegration of a jet was most rapid when

$$\lambda = 4.508 \times 2a \qquad (2)$$

where λ = wavelength of the disturbance

a = the radius of the jet.

He later modified his theory to include the effects of viscosity (Rayleigh *1892*). Weber (*1931*) continued Rayleigh's work and described this relationship as

$$\lambda = \pi d_j \left(2 + \frac{6\eta}{(d_j \varrho \sigma)^{1/2}}\right)^{1/2} \qquad (3)$$

where d_j = diameter of the jet

η = absolute viscosity of the liquid

ϱ = density of liquid

σ = surface tension.

This equation reduces to $\lambda = 4.44\ d_j$ for relatively non-viscous liquids such as water (Bouse *1975*).

Schneider and Hendricks (*1964*) reported that the size of the drop can be controlled over a limited range by altering the frequency of modulation of the capillary and by varying λ between the empirical limits $7a < \lambda < 14a$. They also noted that drive frequencies lower than the fundamental drive frequency result in the production of several homogeneous drop streams of different diameters, each a function of a different harmonic of the fundamental drive frequency. Schneider et al. (*1967*) later extended, with experimental data, the upper limit of λ to 36a and showed, on the basis of the laws of conservation of mass and momentum, that the relationship for r_d can be expressed as

$$r_d = (3a^2 v_j / 4f)^{1/3} \qquad (4)$$

where r_d = radius of the drop

a = radius of the jet

v_j = velocity of the jet

f = driving frequency.

Thus, they demonstrated for water drops the relationship among f, λ, and r_d.

Dabora (*1967*) studied drop production in water, kerosene, and diethylcyclohexane (DECH) and concluded that the optimum frequency of disturbance in any liquid jet at the smallest possible velocity could be expressed as

$$f = 0.627\ (\sigma / \varrho d_j^3)^{1/2} \qquad (5)$$

where f = frequency of maximum instability

σ = surface tension of liquid

ϱ = density of liquid

d_j = diameter of the jet

Bouse et al. (*1974*) found no significant difference between experimental data and drop sizes predicted from measured flow rate and the disturbance frequency. They calculated drop diameters using the equation

$$D = (6Q_s / \pi f)^{1/3} \qquad (6)$$

where D = drop diameter

Q_s = flow rate

f = frequency of disturbance

Dimmock (*1950*) applied the Rayleigh theory of cyclic disturbance using a glass capillary vibrated with an electromagnet. He used an alternating current to produce uniform streams of drops 0.01 to 0.3 mm in diameter. Magarvey and Taylor (*1956*) designed two drop-producing apparatuses creating drops 0.5 to 20 mm in diameter. Their "Type A" apparatus used an audio speaker system directly connected to a capillary to provide the cyclic disturbance. Drop diameters from 0.5 to 2.5 mm were created with reported drop diameter fluctuations of less than 1 percent. Ryley and Wood (*1963*) used hypodermic needles vibrated by an adjustable frequency motor to produce drops 0.30 to 1.35 mm in diameter as did later investigators (Gunn *1965*; Lindblad and Schneider *1965* [0.050 to 0.700 mm]; Mason and Brownscombe *1964* [>0.12 mm]; Mason et al. *1963* [0.03 to 1.0 mm]; McCool et al. *1978* [0.08 to 1.0 mm]; Schotland *1960* [0.30 to 1.0 mm]; Williamson and Threadgill *1970*, *1974* [0.109 to 0.228 mm]). Schneider and Hendricks (*1964*) used a piezoelectric transducer to induce a cyclic disturbance to a capillary to produce drops 0.05 to 2 mm in diameter.

Similar devices are described by Schneider et al. (*1965*, *1967*) and Adam et al. (*1968*) [0.12 to 1.0 mm] that produce droplets that could be charged by passing through charged rings and later deflected by electrostatic means

to produce isolated drops for study. Strom (*1969*) used an electrostrictive disk to cause a capillary, and hence the resulting jet, to vibrate and create drops 0.015 to 0.040 mm in diameter.

In an alternative method, a cyclic disturbance was induced in the liquid itself. In the Magarvey and Taylor (*1956*) "Type B" dropper, either an oscillator-driven earphone or a plunger driven by an electric motor pulsed the water "inline" to produce drops as large as 20 mm in diameter. In a similar system designed by Atkinson and Miller (*1965*), inline water pumps provided cyclic pulses to an already pressurized water supply, producing drops 0.40 to 1.54 mm in diameter. Winn (*1969*) and Abbott (*1969*) later used that system with similar results. Magarvey and Curry (*1966*) used an audio-oscillator driven earphone with a watertight diaphragm to produce drops 4.0 to 20.0 mm in diameter in a pressurized system. Similar systems were used by Dabora (*1967*) [0.29 to 0.95 mm] for water, kerosene, and DECH, and by Adam et al. (*1971*) [0.012 to 2.0 mm] for water.

Bouse (*1974*) and Bouse et al. (*1974*) [0.13 to 0.63 mm] used pinhole orifices drilled into orifice plates to produce jets for droplet production. Bouse (*1975*) studied the atomization process of tapwater, ethanol, glycerol-water, glycerol-ethanol, diesel oil, and paraffin oil. He found that the ratio of the number of satellite drops to the number of major drops increased with orifice enlargement. Calculated and measured drop diameters were linearly related. The minimum and maximum cyclic frequencies used in drop production were linearly related to the Weber frequency (eq. 3), the jet velocity, and the logarithm of the dynamic pressure. A water-pulse system coupled with a linear-acceleration system was developed by McTaggart-Cowan and List (*1975*) to bring drops to their terminal velocity within a very short distance.

A cyclic disturbance can also be induced in a liquid jet by use of a magnetostrictive nickle rod that lengthens and shortens in response to an alternating current. Roth and Porterfield (*1970*) [>0.2 mm] placed the rod directly over small holes (0.15 to 0.38 mm in diameter) drilled into an orifice plate. Schwenn and Sigel (*1974*) [0.15 to 0.40 mm] placed the rod over ruby stones pierced with holes 0.10 to 0.14 mm in diameter. Subsequent vibration of the rod at its fundamental longitudinal mode produced the cyclic disturbance in the jet and hence caused the water droplets. The drop size is limited by the frequency at which the rod vibrates, but this limit can be overcome by changing the orifice diameter. Cataneo et al. (*1971*) and Bouse et al. (*1974*) reported using a piezoelectric crystal as an inline source of cyclic disturbance, with a pinhole (0.056 to 0.324 mm) to produce drops 0.13 to 0.63 mm in diameter.

Electric Charge or Atomization

Rayleigh (*1882*) predicted that a charged water drop would remain stable so long as

$$T > Q^2/16\pi a_o^3 \qquad (7)$$

where T = cohesive force, units not mentioned

a_o = radius of the sphere, units not mentioned

Q = charge of electricity, units not mentioned.

An increase of the charge would result in an unstable situation in which water drops exit the water body as described in theory by Kim and Turnbull (*1976*), Levine (*1971*), Melcher and Warren (*1971*), and Zeleny (*1917*). Vonnegut and Neubauer (*1952*) discovered that application of 5 to 10 kv alternating or direct current to a liquid in a small capillary produced a stream of uniform drops about 0.1 mm in diameter. By increasing the voltage and introducing a ground wire to the vicinity, drops approximately 0.001 mm in diameter could be produced (Neubauer and Vonnegut *1953*). Drozin (*1955*) found that drops could not be electrically produced from liquids with very low conductivity. Kim and Turnbull (*1976*) [0.020 to 0.090 mm] sprayed drops of insulating (low conductivity) liquids by mounting a sharp needle in the capillary in such a way that the sharp end protruded from the capillary. A high voltage is applied to the needle, and the charged liquid goes out the end of the capillary. This technique overcame the difficulty encountered by Drozin; the needle injects charge carriers into the liquid to build up the high surface charges needed to electrically atomize and produce droplets. Other investigators using electric charge or atomization include Hendricks (*1962*) [0.0002 to 0.020 mm (octoil)], Hogan and Hendricks (*1965*), Nifuku and Vonnegut (*1975*) [0.2 to 5.1 mm (water)], Pfeifer and Hendricks (*1967*) [<0.01 mm (octoil and glycerine)], Saint-Hilaire and Szili (*1977*) [0.010 to several tenths mm (oil)], and Sample and Bollini (*1972*) [0.060 to 0.50 mm].

Rotating Disk

Walton and Prewett (*1949*) and May (*1949*) fed a liquid to the surface of a rotating disk, and centrifugal force produced uniform drop sprays. Walton and Prewett [0.015 to 3.0 mm] used both a motor-driven disk and an air-spun top, while May [0.015 to 1.5 mm] improved the air-spun top device. Drop size from these devices is defined by

$$d = k(T/D\varrho)^{1/2}/\omega \qquad (8)$$

where d = drop diameter

k = constant

T = surface tension of liquid

D = diameter of the disk

ϱ = density of the liquid

ω = angular velocity of the disk

Drops are flung off and deposited in a circular pattern around the sprayer. The air used in spinning the disk and/or the trajectory of the drops helps to separate extraneous drops from the drops of the size sought.

Hanging Yarn

Yarn has been used as a drop-forming material. Ellison and Pomerene (*1944*) constructed a rainfall simulator using cheesecloth draped over a chicken wire support with yarn attached to the resulting depressions in the cloth. Drops 3.5 and 5.1 mm in diameter were reported with a variation of ±6 percent. Goodman (*1952*) reported similar results. Woo and Brater (*1962*) concluded that the size of the drops produced by this method is a function of the size of the wire mesh, the thickness of the cloth, the degree of middle depression, the surface tension, and the diameter of the yarn.

Miscellaneous Methods

Stuhlman (*1932*) described the mechanics of effervescence in which air bubbles, breaking through the surface of water, create a cavity in the surface that, upon collapsing, ejects one or more drops. Blanchard (*1954*) found that these droplets rise to a characteristic height, which is a function of their size, and that drops 0.002 to 0.5 mm are easily reproduced by the method.

Dennis (*1968*) described a simple apparatus consisting of a wire attached to a metal block. Drops of water are attached to the wire and the block is allowed to fall and is abruptly stopped at a designated velocity. The specified drop size is attained by trial and error. In a similar system, described by Freier (*1960*), a continuous water supply is attached to a capillary embedded in an iron slug. The slug is fitted into a 110-volt solenoid with a soft iron core. An alternating current then shakes out drops of uniform size. Drops of 4.9 to 5.0 mm in diameter were reported.

Uniform drop streams can be produced by a reed entering and withdrawing from a water surface. Rayner and

Table 1.—*Uniform water drop production techniques*

Method	Reference	Range in drop diameter (mm)
Capillary drip	Adams et al. *1957*	5.56
	Bentley *1904*	2-4
	Bubenzer and Jones *1971*	2.2-4.9
	Ekern and Muckenhirn *1947*	2.75-5.80
	Hardy et al. *1960*	>0.002
	Laws *1941*; Laws and Parsons *1943*	1.17-6.1
	Mutchler and Moldenhauer *1963*	3.0-5.8
	Römkens et al. *1975*	2.7
	Wang and Pruppacher *1977*	1.7-6.7
Axial airflow	Buckholz *1957*	0.3-1.6
	Buckholz and McPhail *1960*	0.045-0.45
	Charwat *1977*	0.2-2.5
	Dingle and Schulte *1962*	0.72-3.13
	Englemann *1963*	0.6-12.0
	Ennis and James *1950*	0.22-1.82
	Gunn and Kinzer *1949*; Kinzer and Gunn *1951*	0.07-5.76
	Hardy *1962*	0.7-3.0
	Lane *1947*	>0.3
	Levvy *1947*	([1])
	Mason and Ramanadham *1953*	0.5-1.25
	Rasbash *1953*	0.6-2.4
	Reil and Hallett *1969*	0.4-2.0
	Samuels and Sparks *1973*	0.1-3.0
Cyclic disturbance of capillary jet	Adam et al. *1968*	0.12-1.0
	Dimmock *1950*	0.01-0.3
	Gunn *1965*	([1])
	Lindblad and Schneider *1965*	0.050-0.700
	Magarvey and Taylor *1956*	0.5-20
	Mason and Brownscombe *1964*	>0.12
	Mason et al. *1963*	0.03-1.0
	McCool et al. *1978*	0.08-1.0
	Ryley and Wood *1963*	0.30-1.35
	Schneider and Hendricks *1964*	0.05-2.0
	Schneider et al. *1965*, *1967*	([1])
	Schotland *1960*	0.30-1.0
	Strõm *1969*	0.015-0.040
	Williamson and Threadgill *1970*, *1974*	0.109-0.228
Cyclic disturbance in liquid supply	Abbott *1969*	([1])
	Adam et al. *1971*	0.012-2.0
	Atkinson and Miller *1965*	0.4-1.54
	Bouse *1974*; Bouse et al. *1974*	0.13-0.63
	Bouse *1975*	([1])
	Cataneo et al. *1971*	0.13-0.63
	Dabora *1967*	0.29-0.95
	Magarvey and Curry *1966*	4.0-20.0
	Magarvey and Taylor *1956*	<20
	Roth and Porterfield *1970*	0.2
	Schwenn and Sigel *1974*	0.15-0.40
	Winn *1969*	([1])

[1]Not presented.

Table 1.—*Uniform water drop production techniques—Continued*

Method	Reference	Range in drop diameter (mm)
Electric atomization	Hendricks *1962*	0.0002–0.020
	Kim and Turnbull *1976*	0.020–0.090
	Neubauer and Vonnegut *1953*	0.001
	Nifuku and Vonnegut *1975*	0.2–5.1
	Pfeifer and Hendricks *1967*	<0.01
	Saint-Hilaire and Szili *1977*	0.010–several tenths
	Sample and Bollini *1972*	0.060–0.50
	Vonnegut and Neubauer *1952*	0.1
Rotating disk	May *1949*	0.015–1.5
	Walton and Prewett *1949*	0.015–3.0
Hanging yarn	Ellison and Pomerene *1944*; Goodman *1952*	3.5–5.1
Effervescence	Blanchard *1954*	0.002–0.5
Vibrating reed	Abbott *1975*	0.020–0.050
	Abbott and Cannon *1972*	0.008–0.26
	Harris *1964*	>0.002
	Rayner and Haliburton *1955*	0.05–0.70
	Rayner and Hurtig *1954*	0.07–0.40
	Sartor and Abbott *1975*	0.042–0.157
	Wolf *1961*	0.010–0.20

Hurtig (*1954*) [0.07 to 0.40 mm] used a vibrating reed impinging on a drop at the end of a capillary. The diameter of drops produced depended on the frequency of vibration and amplitude of the reed and the flow rate of the liquid. Wolf (*1961*) [0.010 to 0.20 mm] identified other factors that affect drop size as depth of reed penetration, diameter of the reed, and the wettability of the material used for the reed tip. This vibrating reed technique was used by Harris (*1964*), who produced drops as small as 0.002 mm, and by Abbott (*1975*) [0.020 to 0.050 mm], Abbott and Cannon (*1972*) [0.008 to 0.26 mm], and Sartor and Abbott (*1975*) [0.042 to 0.157 mm]. Rayner and Haliburton (*1955*) used rotating blades of several sizes and shapes to detach drops from a water stream. The blades, just touching the stream surface, created drops 0.05 to 0.70 mm in diameter.

Methods for Catching and Measuring Drops

The drop-catchment and drop-sizing methods reviewed here include filter and Ozalid paper, flour pan, photo-optical, magnesium oxide, oil catchment, momentum recorders, photographic, and weighing. Methods with filter and Ozalid papers are simple but tedious. Unless the paper is continuously moved under an aperture, they are useful only for natural rainfall of low intensity with small drop sizes because splash overlap causes problems. Oil catchment and weighing are useful for calibration of artificially formed drops. Flour is simple and useful for a wide range of drop sizes. Photo-optical systems and photographic techniques are more complex and difficult to use, partly because light conditions are critical and must be carefully controlled. Magnesium oxide on slides is used for very small drops, down to diameters of about 0.010 mm. Momentum recorders are indirect measuring devices from which drop sizes can be determined.

Filter Paper

The oldest method of measuring and recording water drops was devised in Europe during investigations into the nature of rain and the drop sizes associated with it (Becker *1907*; Defant *1905*; Lenard *1904*; Wiesner *1895*). Neuberger (*1942*) and Laws and Parsons (*1943*) list many of those early European techniques. A raindrop that hits the filter paper leaves a circular spot that is rendered permanent by a dye. The radii of the drop (r) and the spot (R) are defined by

$$h = (4/3)(r^3/R^2) \tag{9}$$

where h is the effective thickness of the paper.

Defant (*1905*) showed that h can vary with drop size even for a given paper. Becker (*1907*), Fournier d'Albe and Hidayetulla (*1955*), and Niederdorfer (*1932*) indicated that the spot radius is a function of the drop velocity at impact. Niederdorfer (*1932*) pointed out that the paper had to be completely dry before use to give a sharp outline of the spot.

Fournier d'Albe and Hidayetulla (*1955*) concluded that the relationship between drop size and spot or splash size could be expressed as:

$$D = aS^b \tag{10}$$

where D = drop diameter

a = 0.47, a constant for the filter paper they used

S = splash diameter

b = 2/3, based on the geometry of a sphere.

Jarman (*1956*) measured drop stains made by several liquids containing Rhodamine G and Waxoline Red on Whatman No. 1 filter paper. He found that b had a value of 0.84 ± 0.02 after 24 to 28 hours and concluded that b is not a constant because it is affected by the properties of the liquid, paper, the period of spreading, impact velocity, and the ratio of drop diameter to the thickness of the paper. Magarvey (*1957*) found that the value of b is not constant over an extended range of drop sizes and that for Whatman No. 2 filter paper, b = 0.75 when drop diameter exceeds 1.5 mm and b = 0.93 when it is less. He also found that for drops less than 3 mm in diameter, velocity changes of up to 15 percent showed no significant change in splash diameter, thus the value for b is independent of the impact velocity within those ranges. For drops larger than 3 mm, velocity changes of up to 25 percent did not significantly change splash diameter, which disagreed with the results of Becker (*1907*), Fournier d'Albe and Hidayetulla (*1955*), and Niederdorfer (*1932*). Magarvey (*1957*) concluded that the filter-paper method is reliable if the filter papers that are calibrated and those that are to be used for sampling are stored and dried under uniform conditions.

Gillespie (*1958*) discussed the spreading of stains produced by several low-vapor-pressure liquids on various types of filter paper and printflex cards. He derived the empirical expression

$$\left(\frac{D}{d}\right)^6 = \left(\frac{D}{C_s h}\right)^2 + \frac{6\beta t}{h^2} \qquad (11)$$

where D = stain diameter

d = drop diameter

C_s = saturation concentration

h = thickness of paper strip

β = rate of radial spreading

t = time.

Gillespie noted that this equation applies only to those drops large enough to penetrate to the under side of the paper and that there is no "final stain size" for these low-vapor-pressure liquids.

Hall (*1970*) reviewed 12 studies in which various methods of recording drop splashes were tested on several types of paper and presented the calibration constants derived in each. He, like Magarvey (*1957*), concluded that values for a and b in equation (10) are sensitive to the drop sizes used in calibration. For accurate and constant filter paper response, all filter paper techniques require careful storage and drying both before and after drop catchment (Hall *1970*; Mason and Andrews *1960*).

Dyes used with the Whatman filter paper include methylene blue (Blanchard *1953*), Rhodamine G and Waxoline Red (Jarman *1956*), blue analine (Magarvey *1957*), and bromocresol green (Mason and Andrews *1960*). Other authors using the filter-paper method include Merrington and Richardson (*1947*) (with their study on the breakup of liquid jets), Marshall et al. (*1947*), and Anderson (*1948*), in studies of rainfall dropsize distribution. Bowen and Davidson (*1951*) and Spencer and Blanchard (*1958*) used rolls of paper to make continuous records of raindrops to study long-term drop distributions in rainstorms.

Two methods similar to the filter-paper method were described by Spencer and Blanchard (*1958*) and Engelmann (*1963*). In the first, a roll of ordinary adding machine paper impregnated with dry methylene blue chloride dye was used. In the second, Ozalid paper, a commercial blueprint-type paper, was used. When drops hit the paper, the dyes move to the edges of the drop so that, when dried and/or developed, a permanent record of the drop splash remains. The Ozalid paper technique was used by Hardy (*1962*) and later by McCool et al. (*1978*) with excellent results in the laboratory and for natural rainfall-drop catchment in low-intensity storms with small drops.

Flour Catchment

Bentley (*1904*), in his study of raindrops and their size distribution, developed the flour-pellet method. Drops, naturally or artificially created, fell into a pan containing 25 mm (1 inch) of fine, sifted, leveled flour. The resulting dough ball, after hardening and drying, was proportional in size to the responsible drop. Small drops produced dough balls of nearly the same diameter as the water drop, while larger drops tended to flatten on impact and produced an oblate spheroid. After the dough balls were dried, they were then sifted through a set of standard sieves and separated into class sizes for further study. Because larger dough balls were flattened, the mass of the dough balls was correlated to the corresponding drop size and a calibration curve was generated. Fortunately, the balls that pass one sieve and are trapped in the next display a more or less constant mass, thus facilitating analysis. The dough balls are then weighed and the mass of the water drops is calculated.

Laws and Parsons (*1943*) used this method to study the relationship between drop size and rainfall intensity.

The pans were exposed to rainfall until they were "moderately covered" and the exposure time was noted. Hudson (*1963*) used an automated system of 10 flour pans set on a rotating table that exposed each pan for 4 seconds to a preset rainfall intensity. The resulting dough balls were then oven dried and separated by nested sieves.

Carter et al. (*1974*) used flour to record drop-size distribution when the filter-paper method proved unable to handle the high-intensity, large-drop-type storms that they studied in the South Central United States. Carter et al. (*1974*) found the raindrop size from the equation

$$D = \sqrt[3]{(6/\pi)\omega} \tag{12}$$

where D = drop diameter in millimeters

ω = average drop weight in mg, found from the weight ratio between dough balls and the corresponding drops.

Tests from a 12.2-m (40-ft) tower indicated that the velocity of the falling water drops did not affect the calibration of the flour.

Kohl (*1974*) studied sprinkler sprays using the flour method. He collected spray samples with circular flour pans, 210 mm in diameter, dried the dough balls, then separated them with a set of 16 sieves for weighing.

Photo-optical

Mason and Ramanadham (*1953*) developed an instrument with a beam of light and a photomultiplier to measure drop sizes. Drops falling through the recording field scatter the light, and a photocell, set at a 20° angle from the light path, records the scatter. The corresponding calibrated voltage produced was measured, classified, and stored electronically in one of eight size groups as small as 0.10 mm. Problems with changes in background illumination affected the return readings, and the device apparently could be used only at night.

A similar device developed by Dingle and Schulte (*1962*) revolved around a pivot and measured a volume of 9.33 L/sec. The photocell was set 30° from the light path to measure scattered light. The extraneous light problem encountered by Mason and Ramanadham (*1953*) was controlled by a light trap surrounding the device. Possible sources of error listed include splash effects, edge effects, nonuniformity in the illumination of the sensitive region, and nonspherical distortion of the raindrops. Results of drop-size distribution recorded from several rainstorms compare closely with the Marshall and Palmer (*1948*) spectra of drop-size distribution vs. rainfall intensity and give credence to the apparatus' reliability. Hardy (*1962*) used that apparatus with a correction factor, based on geometric considerations and experimental observations, to describe raindrop-size distribution.

Nathan (*1963*) described another light system that samples an area of 2500 mm^2 and has a 12-channel recording system for 12 drop-size ranges from 0.2 to greater than 4.0 mm diameter. Bradley and Stow (*1974*a, *1974*b, *1977*) used an He-Ne laser source to measure raindrop sizes from 0.24 to 4.0 mm diameter. Wang et al. (*1977*) used an He–Ne laser with two horizontal inline detectors coupled with an oscilloscope to determine path-averaged rainfall velocity from the attenuation of the beam. By use of the relation between drop size and terminal velocity that was developed by Gunn and Kinzer (*1949*), drop sizes and hence the rainfall rate and drop-size distribution could be determined.

Wang et al. (*1979*) later modified their device to measure the rainfall-induced irradiance of the laser over a 200-m path and again used path-averaged terminal velocities to determine rainfall rate and drop-size distribution. Both devices produced results that were expected by the Marshall-Palmer distribution and were verified by measurements on filter paper and flour and by the relation between rainfall intensity and drop-size distribution.

Glass Slides and Photographic Plates

To record drops extremely small in diameter, May (*1950*) developed a method in which glass slides were coated with magnesium oxide smoke. When droplets greater than 0.020 mm diameter collected on the slides, craters were created such that the ratio of drop diameter to crater diameter was 0.86. The method was found accurate for any of seven liquids tested. The method failed for drops below 0.010 mm diameter. Burgoyne and Cohen (*1953*), Rayner and Haliburton (*1955*), and Wolf (*1961*) studied drops up to 0.10 mm in diameter using magnesium oxide, microscopes, and photography to measure and record drop sizes. Hedden (*1961*) used plain glass slides to study drop sizes of pesticide spray. The slides were exposed for short times to water spray containing a dye, were dried, and the resulting spots were measured with an optical comparator. The spots were classified into 15 size ranges of less than 0.02 to greater than 0.6 mm.

A method related to the use of magnesium oxide-coated slides was described by Sivadjian (*1957*) for sampling rain and cloud drops. Hygrophotographic plates are prepared from exposed and developed photographic plates.

Water drops leave a yellow image on the plates. Drops larger than 0.10 mm are caught with oil-covered plates to avoid shattering.

Oil Catchment

Catching drops in a low-density, immiscible liquid provides an excellent opportunity to preserve small drops for study at a convenient time after catchment. Fuchs and Petrjanoff (*1937*) and May (*1945*) collected samples on glass slides with a freshly melted mixture of vaseline and light mineral oil. Drops maintain their size and spherical shape for many hours in a humid atmosphere without evaporation. The collected drops are then sized with a measuring microscope.

On glass slides and in glass immersion collection cells, authors since have used Apiezon Oil A (Lane *1947*), vacuum pump oil (Englemann *1963*; Gunn and Kinzer *1949*; Kinzer and Gunn *1951*; McCool et al. *1978*), paraffin oil and hydraulic fluid mixture (Dimmock *1950*), hydrocarbon solvent (Cheng and Cross *1975*; Tate *1961*; Tate and Janssen *1966*), silicone oil (Reil and Hallett *1969*; Samuels and Sparks *1973*), and an anisole-mineral oil mixture (Williamson and Threadgill *1970*, *1974*). Tate (*1961*) used drops of dyed water to enhance photographic inspection and measurement. Errors are introduced by shattering of large drops from high impact velocity (Tate *1961*), evaporation of drops not penetrating the collection liquid (Fuchs and Petrjanoff *1937*), and failure of very small drops to impact on the immersion cell (Tate *1961*).

Momentum Recorders

Drop sizes have also been studied by the use of impact-recording instruments. Cooper (*1951*) used an airborne microphone whose responses had been calibrated into six classes of drop diameter. Errors are introduced by the lack of uniform response across the microphone diaphragm. Detection of small drops is difficult because of the background noise level associated with large diaphragms and the shattering of large drops on impact (Mason and Ramanadham *1953*). Katz (*1952*) combined a capillary collector, a condenser microphone, and a flowmeter to make a self-calibrating device. The calibrated response of the drop momentum at impact is recorded electronically. The sum of the drop sizes recorded should equal the total volume of the water collected.

Joss and Waldvogel (*1967*) developed a rainfall spectrometer, the RD–69, that acts as a momentum recorder for drops between 0.3 and 5.5 mm in diameter (see also Joss and Gori (*1978*)). The device consists of a 5000-mm^2 styrofoam body connected to a transducer and sensing coil. The sensing coil produces a voltage that, driving another coil, returns the sensor body to its original position. The device was used by Federer and Waldvogel (*1975*) to study raindrop-size distributions. Kinnell (*1976*) disputes the manufacturer's (Distromet Ltd. of Switzerland) claim of 5 percent accuracy and shows that the disdrometer is sensitive to drop velocity and shape and that, under certain conditions, that is, appreciable air movements or drop shape fluctuations, would provide inaccurate measurements. Joss and Waldvogel (*1977*) defend their device by pointing out that it was designed for natural precipitation events and not severe situations such as Kinnell used and that the effects of drop-shape oscillations would produce only a 2 percent error in measured drop diameter for drops falling at their terminal velocity. Martner (*1977*) used the disdrometer, with only limited success, to calibrate radar measurements of drop-size distributions in two thunderstorms.

Photography

Drop sizes have been recorded by photography; either a print or the negative is used depending upon lighting (Abbott *1975*; Bouse et al. *1974*; Charwat *1977*; Hendricks et al. *1964*; Jones *1959*; Jones and Dean *1953*; Laws *1941*; McDonald *1954*a, *1954*b; Roth and Porterfield *1965*, *1970*; Sartor and Abbott *1975*). Drop sizes are measured directly or against a calibrated background. Two problems in photographic methods are a lack of contrast needed to distinguish drop edges and drops that are not within the focal plane and produce blurred images (Pfeiffer *1963*). High-speed photography, along with a diffused reflected light that produces a sharp contrast between a drop and its surroundings, was used by Pfeiffer (*1963*) with excellent results.

Weighing

With drops large enough to be counted individually and produced in uniform size, a sample set may be collected and weighed for calculation of the average mass per drop. The average diameter can then be determined. Weighing must be accurate and evaporation losses must be minimized by covering the sample and/or weighing immediately after collection. Authors using this technique include Lammers (*1969*), Laws (*1941*), Levvy (*1947*), Magarvey and Taylor (*1956*), McCool et al. (*1978*), Mutchler (*1965*), and Winn (*1969*).

Coated Screens

Screening was used by Blanchard (*1949*) and the Mount Washington Observatory (*1951*) to study drop size. The screens were impregnated with a soot or sugar mixture. When exposed to rainfall, the drops removed the recording material as they passed through the screen, leaving behind measurable records of the drop sizes.

Summary

Uniformly sized water drops from 0.001 to 20 mm in diameter can be produced by the methods described in this paper; the desired drop size dictates the production method. More than one technique for producing water drops may be required for calibration of sizing methods to determine drop-size distribution of natural rain in order to encompass the range of natural drop sizes.

Various methods can be used to measure raindrop or water drop diameter. Selection of a method depends upon the rainfall intensity or rate of drop encounters and upon the resources of the investigator. A range of techniques from the simple to the complex was included and discussed.

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